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Method of Determining the Actual Form of the Tool Edge from Chips*

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A method has been proposed by which a variety of actual cutting edge forms in cutting can be estimated from the information obtained with the observation of longitudinal section of chips only, and graphs illustrated by this method are presented. The formulas by which the actual rake angle in cutting can be calculated with the lattice pattern or the fibrous structure in the work deformed are induced. By applying these methods, the shape of built-up edge, the actual edge of restricted tool, in cutting, and so forth have been determined. And then, experiments have been carried out to substantiate these methods. The results coincide with the theory.

cutting, chip, actual rake angle, metal flow, built-up edge

1. Introduction

In order to make a precise study of the phenomena which take place at the edge of a tool during cutting, it is necessary to determine the actual form of the tool which is being used. Often, the edge form which is actually involved in cutting differs from the geometry of the tool itself. In other words, chip does not necessarily flow out exactly along the rake face of the tool even in the cases of tools with land, the SWC tools, and the restricted tools; of course, this is particularly true in case of built-up edge or where welds have built up on the rake face. If the purpose is only to judge the occurrence of a built-up edge, the inspections of the tool rake face used or the observations of the back side of chips will give a sufficient answer. The method used to examine the precise form of the built-up edge or the actual form of the edge in any other case, however, includes quick-stopping of cutting action and grinding the cutting area to examine it with a microscope, or photographing the cutting state by a high speed camera, etc. Although these methods are supposed to allow precise examination of the form of cutting edge, they still leave some problems. For example, the quick-stopping method involves a problem concerning the stopping speed in higher cutting test. Even when the speed is not a problem, the observation is restricted to the state at a single moment, and in cases of such built-up edges, where the form varies from one moment to the next, therefore, it is necessary to collect many samples to obtain unbiased information. This involves much labor and time. When high-speed photo-

graph is used, the observation is restricted to the side of cutting area and it is impossible to observe what is going on in the chip formation zone, so a misjudgment may occur.

In this report, authors propose a method which can determine an actual form of the cutting edge during orthogonal cutting from the information of chip only, which is obtained by observing ground surface of a longitudinal section of chips, and experiments have been carried out to substantiate this method. Here, the same grinding processes are used as the quick-stopping method and chips are observed with a microscope. However, since many values can easily be obtained from various parts of the chips, it is not necessary to spend so much labor in collecting and examining samples. Another advantage of this method is that it allows inspection along the cutting edge by selecting appropriate grinding positions in width of the chip. This is not possible with the high-speed photograph method.

2. Determination of actual rake angle

Many reports^{(1)~(6)} indicate that the direction of metal structure flow in the longitudinal section of the chip (the direction of primary flow, whose angle to the tangent of the chip on the side of rake face is hereafter denoted as ϵ_1) is determined by the rake angle, cutting ratio, cutting forces, and so forth. Thus, it must in turn be possible to determine the actual rake angle (hereinafter called actual rake angle γ_a) for releasing the chip from the calculation based on information from the chips alone, such as the angle ϵ_1 , the cutting ratio, and so forth. First, a study was made to determine whether the results of previous research in this area can be applied in this manner. These results and the feasibility of applying them to this subject were shown in Table 1.

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Table 1 The studies referenced on direction of the primary flow in chip

Investigator	Factor	The results and their applicability to this object
H.Opitz H.Hucks	rake angle cutting ratio cutting force	the various angles calculated. impossible to accurately determine the relationship between the cutting force and the position of chip.
K.Okushima K.Hitomi B.Shaffer	rake angle cutting ratio (cutting force)	inclination of the longitudinal lines of lattice. essentially differ from the primary flow in the chips.
K.Taniguchi	rake angle shear strain	direction of the major axis of an ellipse on the chip. same condition as Hill's one
R.Hill	rake angle shear strain	the direction of the maximum tensile strain. as the Second Method in this paper.
A.розенберг А.Еремин	rake angle cutting ratio	the direction of the maximum shear strain. as the First Method in this paper.

According to Opitz et al.⁽¹⁾, ϵ_1 is determined in each case from the rake angle, cutting ratio and cutting force. In the case under study, where the cutting tool has a built-up edge, the cutting force changes greatly with growth or fall-off of the built-up edge. Since it is almost impossible to accurately determine the relationship between the cutting force and the position of chips, the above method cannot be applied to this subject. The other research calculates ϵ_1 from the rake angle and cutting ratio (including shear strain) alone, and thus it can be applied to this subject. Okushima and Hitomi⁽²⁾ and Shaffer⁽³⁾ define ϵ_1 as the inclination of the lines in the chip, which are drawn on the side face of work-piece so as to make a lattice-pattern with cutting direction (hereinafter the angle formed between this inclined lines and tangent to the chip on the rake face is called ϵ_2). However, the above ϵ_1 , ϵ_2 are essentially different from each other, although they may assume proximate value under certain condition. Since this ϵ_2 differs from the object of consideration of this subject, it cannot be used. Those ϵ_1 and ϵ_2 will be discussed precisely in section 2.3. Rosenberk et al.⁽⁵⁾ define ϵ_1 as the direction of a deformed portion of material which previously existed in the plane on which the maximum shear stress was exerted (this plane makes a constant angle of $\pi/4$ with the shear plane) in a single shear-plane model. Here, authors refer to the method which employs this idea as the First Method in this paper. Hill⁽⁶⁾ says that the direction of the maximum tensile strain due to shear strain

γ^* equals to ϵ_1 , and Taniguchi⁽⁴⁾ has reached the same conclusion as Hill by drawing small circles on the side face of the work in advanced and examining the direction of the major axis of ellipses which are made from the circle when it is deformed in the chips. Authors refer to the method and employ this idea as the Second Method. In the section 2.3, it is proved that the First Method is superior to the Second one.

2.1. Assumption in determining actual rake angle γ_a

This research includes cases where built-up edges are formed and in such cases a fluctuating overcut usually occurs. Cases happen especially with nose type built-up edges, where the cutting edge has a large radius which is thought to increase the shear zone. Determination of the actual rake angle γ_a is desirably as simple and accurate as possible in practical use. Mainly the thickness of the chip and the value of ϵ_1 were therefore used as data. The other data, that is the angle of secondary flow, the thickness of the flow's layer and so forth, were appropriately selected to determine the nose radius, as is described later.

Accordingly, the following assumptions were made to allow the problems to be studied as combinations of the single shear plane model.

When overcutting occurs, an overcut depth Δ is added to the set depth of cut t_1 as shown in Fig.1, resulting in an ac-

Fig.1 Relationship between the set depth of cut and the overcut

Fig.2 Cutting model with round edge tool

tual depth of $(t_1 + \Delta)$. In the case of normal orthogonal cutting, the value $(t_1 + \Delta)$ can be determined from measurements taken before and after cutting. In the case of continuous cutting, however, such as quasi-orthogonal cutting on the end surface of cylinder, such measuring is impossible. In the latter case, therefore, it is assumed that the phase difference of overcut can be neglected as far as average actual depth of cut is concerned. Thus, the position of the cutting line can be regarded as having a parallel movement by the amount of overcut Δ ; so the actual depth of cut is considered the same as the set depth of cut.

Next, the cutting model shown in Fig. 2 is considered for the case of a rounded edge. Here it is assumed that an extension of the shear zone due to roundness of edge is concentrated in the vicinity of the edge and that the primary flow is formed by the single shear plane CB. That is, the upper layer t_{1u} of the depth of cut t_1 is sheared along the shear plane CB, forming the upper layer t_{2u} of chip, while the lower layer t_{1l} is sheared off in the shear zone A'CD as the lower layer t_{2l} of the chip; the latter will be explained precisely in Fig.18; thickness ratio of the layers satisfies $t_2/t_1 = t_{2u}/t_{1u} = t_{2l}/t_{1l} = \lambda$ (reciprocal of the cutting ratio). Hence, it is assumed that the edge roundness can be neglected, that the total chip thickness t_2 may be used for computing the actual rake angle γ_a , and that the relational expression among ϵ_1 , γ_a and λ may be considered with the cutting model which has a single shear angle ϕ_u .

Fig.3 Generation of ϵ_1 in a single shear plane model

Fig.4 Nomogram for θ_1 by the quick-stopping photograph

2.2. Relation between actual rake angle γ_a and primary flow angle ϵ_1

In this section Figs.3(a) and 3(b) are used to explain the First Method and the Second Method respectively, under the assumption that ϵ_1 of the previous section is generated in a single shear plane.

In the First Method, a square element (ACED) of the work which has one side lying on the shear plane is transformed into a chip in the form of a parallelogram (ACFG). The direction of maximum tensile stress AE ($\angle CAE = \theta = \pi/4$) due to maximum shear stress operating during the transformation becomes AF in the chip and forms the primary flow angle $\angle FAN (= \epsilon_1)$. From Fig.3(a), these relations become, as follows,

$$\begin{aligned} AD &= t_1 / (\cos \phi_u + \sin \phi_u / \tan \theta_I) \\ \tan \angle FAD &= \tan \{ \epsilon_1 + (\phi_u + \gamma_a) \} \\ &= (\cos \phi_u \tan \theta_I + \sin \phi_u) / (\tan \theta_I \sin \phi_u) \\ &\quad + \tan (\phi_u - \gamma_a) \\ \tan \{ \epsilon_1 + (\phi_u - \gamma_a) \} &= \tan (\phi_u + \gamma_a) + \cos \phi_u + \cos \theta_I \\ &\dots\dots\dots (1) \end{aligned}$$

Fig.5 Verifying value of θ_1 obtained by the quick-stopping photographs

Fig.6 Relationship among γ_a , ϵ_1 and λ with the First Method

The real edge form may be varied depending on various factors such as built-up edge, matter adhering to the edge point, the land, and the cutting speed. Whether the relation that $\theta_I = \pi/4$ is always applicable or not is checked as follows.

The formula (1) was transformed as follows:

$$\theta_I = \cot^{-1} [\tan\{\varepsilon_1 + (\phi_u - \gamma_a)\} - \tan(\phi_u - \gamma_a) - \cot\phi_u] \dots\dots\dots (2)$$

Then γ_a , ε_1 and ϕ_u were measured from various quick-stopping photographs according to the model shown in Fig.2, and the results were substituted into (2) to determine θ_I . If it is difficult to measure ϕ_u accurately when measuring the values from the quick-stopping photographs, it may be calculated from the formula (3) below.

$$\lambda = t_2/t_1, \quad \phi_u = \tan^{-1} \{\cos\gamma_a / (\lambda - \sin\gamma_a)\}$$

$$\theta_I = \cot^{-1} \left[\frac{\lambda \cos\gamma_a \{\lambda \cos\gamma_a - \tan\varepsilon_1 (1 - \lambda \sin\gamma_a)\}}{\tan\varepsilon_1 (1 - 2\lambda \sin\gamma_a + \lambda^2) - \lambda \{\lambda \cos\gamma_a - \tan\varepsilon_1 (1 - \lambda \sin\gamma_a)\} (\lambda - \sin\gamma_a)} \right] \dots\dots\dots (3)$$

Fig.4 is a nomogram for formulas (2) and (3), and the approximate value of θ_I can be determined using this nomogram. The quick-stopping photographs used for verification of θ_I include those taken by Hoshi et al.⁽⁷⁾⁽⁸⁾ and Heginbotham⁽⁹⁾ in addition to those by the authors.

These photographs were obtained by the cutting of S45C, S35C, S25C and S10C carbon steel and α and β brass, and all photographs were taken as data regardless of the existence of built-up edges. The results of verifying θ_I in this manner are shown in Fig.5. The cutting speeds in the data were chosen in a very low range of 0.30 m/min to 150 m/min, and actual rake angles were from -6° to 48° , where a large wedge-type built-up edge was observed. As it is clear from Fig.5, θ_I can be regarded as approximately equal to $\pi/4$. Thus, when $\pi/4$ substituted for θ_I , formula (1) becomes,

$$\tan\{\varepsilon_1 + (\phi_u + \gamma_a)\} = \cot\phi_u + \tan(\phi_u - \gamma_a) + 1 \dots\dots\dots (4)$$

and

$$\lambda(\lambda + \cos\gamma_a - \sin\gamma_a)(\lambda \cos\gamma_a - \tan\varepsilon_1 + \lambda \tan\varepsilon_1 \sin\gamma_a) - \tan\varepsilon_1 (1 - 2\lambda \sin\gamma_a + \lambda^2) = 0 \dots\dots\dots (5)$$

relational expression (4) and (5) can be represented in the graph as illustrated in Fig.6.

In the Second Method, a layer with a unit thickness of 1 is presumed of the shear plane as shown in Fig.3. For segments l_n and l_m in this layer, l_n is compressed to l_n' , and l_m is extended to l_m' when the layer is subjected to shear strain γ^* . That is, there is direction of maximum tensile strain due to shear strain γ^* , and if l_m' lies in the direction of maximum tensile strain, and the angle between l_m' and shear plane is θ_{II} , the following relationship exists⁶.

$$\gamma^* = 2 \cot 2\theta_{II}$$

In the Second Method, the direction of l_m' is assumed to correspond to ε_1 . On the other hand, the shearing strain is,

$$\gamma^* = \tan(\phi_u - \gamma_a) + \cot\phi_u,$$

so that, ε_1 is expressed as follows,

$$\varepsilon_1 = \pi/2 - 1/2 \cot^{-1} [1/2 \{\tan(\phi_u - \gamma_a) + \cot\phi_u\} - (\phi_u + \gamma_a)] \dots\dots\dots (6)$$

However, the results of the formula (6) do not coincide with measured values so accurately as with those of formulas (4) and

(5), then graphing of formula (6) is omitted.

2.3. Comparison of the First and Second Methods

Using the quick-stopping photographs methods for carbon steel and brass, a comparison was made to determine which of the First and the Second Methods better coincides with actual cutting data. In all the cases (regardless of whether a built-up edge was formed), ε_1 and t_2 were measured from the chip immediately after it was separated from the rake face of the tool or from built-up edge in the quick-stopping photograph. The actual rake angle was then calculated from formula (5) according to the First Method as γ_{aI} and from formula (6) according to the Second Method as γ_{aII} . On the other hand, the actual rake angle γ_a of the edge was measured from the

(a) β -Brass $\times 10$

$V = 0.30 \text{ mpm}$, $\gamma_t = 0^\circ, 30^\circ$, $\gamma_a = 10^\circ$, $\gamma_{aI} = 10.5^\circ$, $\gamma_{aII} = 12.5^\circ$

(b) S45C $\times 10$

$V = 18.2 \text{ mpm}$, $\gamma_t = 10^\circ$, $\gamma_a = 39.5^\circ$, $\gamma_{aI} = 40^\circ$, $\gamma_{aII} = 44^\circ$

Fig.7 Comparison of γ_a with γ_{aI} and γ_{aII} measured by the quick-stopping photographs

photograph and was compared with γ_{aI} and γ_{aII} . Examples of the quick-stopping photographs are shown in Fig.7. Fig.7(a) shows cutting results with a tool provided with double rake angles of (0° and 30°), where a small wedge-type built-up edge has grown. The measured values of γ_a is 10° , which coincides better with γ_{aI} . Fig.7(b) shows a case in which a nose-type built-up edge has grown, and the measured value of $\gamma_a=39.5^\circ$ also coincides with γ_{aI} better than γ_{aII} in this case. Comparing measured values with calculated value in the same way for both the First Method and the Second Method, the results obtained are shown in Fig.8. As seen in Fig.8, the values calculated by the First Method coincide better. With the Second Method, calculated γ_{aII} becomes too large as γ_a increases, making conformity poor. The reason for this is, perhaps that the shear angle ϕ_u increases and γ^* becomes smaller as γ_a becomes larger, and that factors other than pure shearing strain in the shear zone, where maximum elongation occurs have

Fig.8 Comparison of measured value γ_a with calculated values by the First and the Second Methods

Fig.9 Graphs to obtain γ_a and ϕ_u by ϵ_1 and λ

Fig.10 Comparison of measured and calculated values of γ_a and ϕ_u by the First Method

greater influence in the First Method than they do in the Second Method. Therefore, the following discussion will be based on the First Method.

Fig.9 is modified graph of Fig.6 on the ϵ_1 - ϕ_u plane, on which ϕ_u , as well as γ_a can be determined from ϵ_1 and λ .

Fig.10(a) shows results of another investigation for the measured values of γ_a and the calculated values of γ_{aI} , and the results obtained by Hoshi⁽²⁾⁽³⁾ and Heginbotham⁽⁹⁾ are shown with those by the authors. This figure also makes it clear that the First Method gives better results than the Second Method. Fig.10(b) shows a comparison of the measured values of shear angle ϕ_u (determined from the quick-stopping method) with the calculated values $\phi_u(\epsilon_1)$ from the graph of Fig.9. It is clear also that the First Method gives better results.

2.4. Angle of lattice line inclination ϵ_2 and angle of fibrous structure inclination ϵ_3 in chips

The viscoplasticity method is applied often in cutting research. The lattice lines perpendicular to the cutting direction show a particular inclination in the chips. Here, it will be shown that ϵ_2 differs from ϵ_1 , as described in Chapter 2. Fibrous structure formed during the roll-

Fig.11 Mechanism of generation of ϵ_1 , ϵ_2 and ϵ_3

Fig.12 Relation among ϵ_2 , γ_a and λ

ing and other processes remains often in the work. As this structure remains yet in the chip after cutting, ϵ_3 , which denotes the angle between the direction of inclination of the fibrous structure in the chip and the tangent of the chip on the rake face, was examined to make it available as a source of information.

Fig.11 shows the mechanism of generating angles ϵ_2 and ϵ_3 together with that of ϵ_1 described previously. That is, AC_1 is the plane which makes $\theta=\pi/4$ with shear plane AB, AC_2 is one of the lines of lattice drawn as previously, and AC_3 is the direction of fibrous structure which makes the angle with respect to the direction of cutting. These yield respectively AD_1 , AD_2 and AD_3 in the chip, and make angles ϵ_1 , ϵ_2 and ϵ_3 with the rake face side in the section respectively. Changing formula (4) gives ϵ_1 and Fig.11 gives ϵ_2 and ϵ_3 as follows.

$$\epsilon_1 = \tan^{-1} \{ \tan(\phi_u - \gamma_a) + \cot \phi_u + 1 \} - (\phi_u - \gamma_a) \dots \dots \dots (7)$$

$$\epsilon_2 = \tan^{-1} \{ \tan(\phi_u - \gamma_a) + \cot \phi_u + \tan \phi_u \} - (\phi_u - \gamma_a) \dots \dots \dots (8)$$

(a) $\gamma_a(\epsilon_2) = 47^\circ$

(b) $\gamma_a(\epsilon_1) = 46.5^\circ$

β -Brass $\times P20$, $V=0.30$ mpm, $\gamma_t=10^\circ, 30^\circ$, $\gamma_a=45^\circ$

Fig.13 The quick-stopping photographs of measured ϵ_2 and ϵ_1 by the same sample

Fig.14 Comparison of $\gamma_a(\epsilon_1)$ and $\gamma_a(\epsilon_2)$ with γ_a

$$\epsilon_3 = \tan^{-1} \{ \tan(\phi_u - \gamma_a) + \cot \phi_u + \tan(\psi - \phi_u) \} - (\phi_u - \gamma_a) \dots \dots \dots (9)$$

Here, ψ is the angle between the cutting direction and the direction of fibrous structure. Formula (8) can be graphed as shown in Fig.12. If Fig.12 is then compared with Fig.6, which shows ϵ_1 by formula (7) in the First Method, the two graphs differ considerably from each other in the range of smaller values of λ where the chips are thin and γ_a is large, but the curves for ϵ_1 and ϵ_2 come close together with increasing λ . This seems to be the reason why a few investigators could not distinguish ϵ_2 (the direction of the inclination of the lattice lines) from ϵ_1 (the direction of the primary flow).

Fig.13(a) is a photograph of the lattice in the chip obtained by the quick-stopping with the work of brass. Fig.13(b) is a photograph of the structure under layer of the latticed surface which was exposed by grinding the same sample. In other words, both are pictures which show ϵ_2 and ϵ_1 for the same sample by different methods. Both $\gamma_a(\epsilon_2)$ calculated by formula (8) with ϵ_2 measured from the deformed lattice pattern in Fig.13(a) and $\gamma_a(\epsilon_1)$ calculated by formula (7) measured from the primary flow in Fig.13(b) agree well with the actual rake angle γ_a at the built-up edge. Fig.14 shows the results of checking the calculated values $\gamma_a(\epsilon_2)$ which were determined in the same manner as Fig.13(a) and 13(b), with the actual rake angle γ_a . As can be seen, agreement between the two is good.

The angle of inclination of the fibrous structure in the chip, ϵ_3 , is expressed by formula (9). An attempt was also made to verify that this angle is available to calculate the angle γ_a with the quick-stopping photographs of S35C carbon steel material. Cutting was carried out in various directions in relation to

Fig.15 The quick-stopping photograph for the work with fibrous structure

Fig.16 Comparison of $\gamma_a(\epsilon_3)$ and $\gamma_a(\epsilon_1)$ with γ_a

the fibrous direction of the material, when the actual $\gamma_a(\epsilon_3)$ was calculated from formula (9) by measuring ϵ_3 , which is inclination of the fibrous structure remaining in the chip (mainly as in the direction of the ferrite band). Fig.15 is the quick-stopping photograph, which shows the case of angle ψ being 150° . The direction shown with a broken line in the figure is the direction of inclination of the fibrous structure remaining in the chip. Fig.16(a) show the comparison of angle $\gamma_a(\epsilon_3)$ (actual rake angle calculated from ϵ_3) and the actual rake angle γ_a , and it is clear that they are in good agreement. If Fig.15 is examined carefully, it can be seen that the pearlite grain in the chip extends in a direction, which is different from ϵ_3 (the direction is shown with a solid line in Fig.15). This direction corresponds to ϵ_1 , and the actual rake angle $\gamma_a(\epsilon_1)$ can be calculated from formula (7). These results are shown in Fig.16(b), and this figure also proves that the use of the First Method for determining the actual rake angle γ_a is more reliable.

If the direction of the fibrous structure is the same as that of cutting (i.e., if $\psi=0^\circ$ or 180°), formula (9) always gives $\epsilon_3=0^\circ$ for any values of γ_a , so γ_a cannot be determined because the direction of the ferrite band is parallel to the lateral group of lattice lines. In these cases, if attention is paid to the direction ϵ_1 in which pearlite grain are extended, γ_a can also be determined by applying formula (7).

2.5. Back-bending of the primary flow

As shown in Fig.17(a), the primary flow in a chip may sometimes bend backward in the center of thickness a little toward rake face¹⁰. This phenomenon occurs always when gaseous oxygen is blown against the cutting edge from the beginning of cutting carbon steel with the speed range in which built-up edge occurs. For this reason, it is thought that a wedge-type built-up edge with a sharp nose edge formed by the effect of oxide films occurs, which is inferred to be Fe_3O_4 having good extrem pressure lubricating ability between the built-up edge and the chip⁽¹¹⁾. Here, the chip cut by the sharp built-up edge with a large rake angle impinges violently against the rake face of the tool

Fig.17 The back-bending in the primary flow and a model for mechanism of the bending

and it is sheared again. This is assured as the wedge-type built-up edge is formed even during dry cutting of brass at a very low speed when the rake angle of the tool is smaller than the actual rake angle of the built-up edge, when the back-bending of primary flow occurs. Similar phenomena are seen in the photographs taken by Hoshi⁽¹²⁾. In the cases of Fig.7(a) and Fig.13, a wedge-type built-up edge has grown, but the back-bending has not occurred. The reason for this is, that the tool providing a double rake angle is used in these cases where secondary rake angle is so large that chips do not impinge against the rake face of the tool it-self.

The mechanism of the back-bending of primary flow can be explained more scientifically by considering shear planes having the angle of ϕ_2 , ϕ_{21} and ϕ_{22} in addition to the ordinary shear angle ϕ_1 , and by drawing line in such a way that the direction of plastic flow in the chip changes successively as the upper and lower layers of the chip pass those shear planes. The measured values in the experiments support this explanation.

3. Determination of the edge radius of built-up edge

In the case of Fig.2, where the built-up edge has a large edge radius, a cutting model is assumed which has a shear zone A'CD in front of the edge. Details of the shear zone A'CD are shown in Fig.18. The secondary flow occurs in this A'CD zone, therefore, the edge radius of the nose type built-up edge can be determined by the measurement of thickness t_{1l} and ϵ_l of the secondary flow as follows.

It is said that secondary flow is generally caused by the friction between the tool and the chip. Even if the cutting edge is sharp, the zone, which extends from just ahead of the tool nose to the part of the chip contacting with the rake face is explained as the secondary flow zone. In cases where nose type built-up edge is formed, the contact length of chip which is the part behind the nose is generally very short (for example, see Fig.7(b)). It is therefore assumed that the friction force at interval DE in Fig.2 influences very slightly the secondary flow and that secondary flow is concentrated in the A'CD zone adhear of the round edge. Assuming that the round part of the

Fig.18 Detail of the shear zone A'CD of the cutting model with round edge

edge is a circular arc of radius R , the arc can be divided into n parts as shown in Fig.18 and each elemental chord considered as the rake face changing the rake angle sequentially for which there is a corresponding shear plane in the zone. As shown in Fig.18, the round part of the edge is divided into n equal parts to form the rake angle $\gamma_{n,m}^R$ ($m=1,2,\dots,n$) of n chords, the secondary flow thickness t_{2l} and corresponding the lower layer t_{1l} of depth of cut is divided into n equal parts respectively, and secondary flow is supposed to occur in each segmental layer as it passes the corresponding shear plane in sequence. For convenience of calculation, only odd values n are used for division, and inclination of the center layer of the secondary flow is denoted by ϵ_l .

The calculated value of ϵ_l is shown in Fig.19. In this figure, $P=t_{2l}/t_1$, $k_a=R/t_1$ (where R is the radius), and ϵ_l is represented using $t_2/t_1=\lambda$ of a parameter where the actual rake angle is assumed as $\gamma_a=40^\circ$. The angle ϵ_l was calculated with an increasing sequential number of divisions. The calculation was stopped and the results were shown when the difference between results corresponding to present number and the previous number of divisions agreed within 1/100 degree of each other.

Fig.20 shows a comparison of the measured values of the edge radius ratio, $k_a=R/t_1$, for the built-up edge with the values $k_a(\epsilon_l)$ calculated using the quick-stopping photographs. As the two values almost coincide with each other, it is

Fig.19 Graph of the calculated value of ϵ_l by γ_a , k_a , P and λ

Fig.20 Comparison of edge radius k_a measured with $k_a(\epsilon_l)$ calculated

considered that this method is effective for determining the edge radii.

4. Method of determining the shape of built-edge from chips

A method of determining the actual rake angle γ_a and the edge radius R from the longitudinal cross-section of chips has been described above. The procedure for determining the form of built-up edge by combining these values is shown in Fig.21 as in the flow chart. The inverse wedge-type built-up edge is one with an inversed triangler shape whose edge has almost no round part. Such built-up edge appears in cutting low carbon steel. Even when it happens that the actual rake angle γ_a is equal to the tool rake angle γ_t , it is dangerous to assumed that no built-up edge has occurred. For example, there are cases in which a built-up edge with an actual rake angle forms which is almost the same as the tool rake angle when medium carbon steel is cut at speeds of tens of meters per min. It is therefore necessary to determine whether a built-up edge has formed, by inspecting the fallen pieces of the built-up edge on the rake face side of chips.

5. Application example

Fig.22 shows an example in which this research was applied to the cutting and the actual rake angle was determined from the chip. In this case, S35C work material with a 48 mm outer diameter and a 20 mm inner diameter was cut with the cemented

Fig.21 Flow chart for determining the actual shape of built-up edge from the observation of chips

Fig.22 Relationship between cutting speed and actual rake angle of tool edge on cut-off machining

carbide cut-off tool 3 mm in width. Ordinary dry cutting and the oxygen supplied jet cutting were performed; in the latter gaseous oxygen was blown along the rake face toward the tool edge with a 1.0 mm diameter nozzle at a pressure of 400 kpa (gage). The back-bending in the primary flow mentioned previously was noticed on the longitudinal cross-section of the chip obtained from cutting at 315 rpm. From the results, it was found that a wedge-type built-up edge formed. When cutting with oxygen jet as the agent was continued in which the back-bending occurred, a crater wear formed on the rake face of the tool. This can be regarded as proving that chips strike violently against the rake face of the tool when the back-bending occurs. By contrast, no crater occurred in other cases.

6. Conclusions

A method of determining the actual form of tool edge has been verified through observations of the longitudinal cross-section of chips produced during orthogonal cutting with supporting experiments, and following conclusions have been reached.

1) It can be assumed that the primary flow in chips occurs in the single shear plane, irrespective of the actual form of the tool edge. The primary flow angle ϵ_1 in the chips is determined by the direction of the plane which makes an angle of $\pi/4$ with the shear plane before the cutting. A formula was derived by which the actual rake angle γ_a in the cutting can be determined by the ϵ_1 and the thickness, obtained from chips only.

2) The angle ϵ_2 , which is made by the longitudinal group (perpendicular to the cutting direction) of lattice lines which are drawn on the side of the work and the tool rake side of face in the chip, is different from the former ϵ_1 . A formula was derived which gives the angle ϵ_2 and it is shown that the actual rake angle γ_a can also be determined from ϵ_2 .

3) A formula was derived which gives the angle ϵ_3 of inclination of the fibrous structure in chips, and it is shown that the actual rake angle γ_a can also be determined from the angle ϵ_3 , except under certain conditions.

4) A wedge-type built-up edge develops when a back-bending occurs in the

primary flow in the chip. This phenomenon is attributed to twice deformation of the chip passing the second shear plane, pushed by repulsion from the rake face of the tool with a wedge-type built-up edge.

5) When a nose-type built-up edge has developed providing a shear zone ahead of the tool edge with a gathering of single shear planes, it may be assumed that the secondary flow can occur mainly in this zone. It was shown that the edge radius of nose-type built-up edge can be calculated from the thickness of chip and the angle ϵ_2 of the secondary flow.

Thus, a method has been proposed by which a variety of actual tool edge forms in cutting can be determined from data obtained with the chip alone.

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- (12) For example, Fig. 6, P. 19 on the reference (8)